

Risk Assessment of Offshore Wind Power Project Investment in the Grid-Parity Era: A Monte Carlo Simulation Approach

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ABSTRACT This study investigates the economic viability and investment risks of offshore wind power projects in the grid-parity era. As offshore wind generation increasingly relies on advanced electromagnetic energy conversion systems, intelligent grid infrastructures, and real-time communication networks for stable power transmission and operational monitoring, accurate investment risk evaluation has become essential for sustainable project development. A stochastic risk assessment framework based on Net Present Value-at-Risk (NPV-at-Risk) and Internal Rate of Return-at-Risk (IRR-at-Risk) is established and applied to grid-parity offshore wind projects using Monte Carlo simulation. The cumulative probability distributions of NPV and IRR are derived to quantify investment uncertainty, while grid-connected electricity volume, feed-in tariff, and construction investment are identified as the dominant sensitivity factors affecting project performance. Based on the simulation outcomes, targeted risk management strategies are proposed for governments, investors, and financial institutions to improve decision-making under uncertain market conditions. The proposed framework provides a practical methodology for evaluating offshore renewable energy investments and offers valuable guidance for intelligent power systems supported by electromagnetic information transmission and smart grid communication technologies.

INDEX TERMS offshore wind power, monte carlo simulation, investment risk assessment, smart grid communications, electromagnetic information transmission

I. INTRODUCTION

IN September 2020, President Xi Jinping announced at the United Nations General Assembly China's commitment to achieving carbon peaking by 2030 and carbon neutrality by 2060. As a crucial component of the renewable energy sector, offshore wind power functions as a pivotal pathway toward these goals. The development of this industry is closely linked to the advancement of high-performance industrial materials, particularly in the production of lightweight, high-strength wind turbine blades and marine structural components using fiber-reinforced composites.

The global ocean-based wind industry continues to expand rapidly. In 2024, newly grid-connected offshore wind capacity reached 8 GW, representing a 26% decline compared to 2023 but still ranking as the fourth-highest annual installation in history. Over the past decade, the compound annual growth rate of installed capacity has averaged 10%. China has maintained its position as the global leader in

newly installed offshore wind capacity for seven consecutive years, accounting for half of the world's total cumulative offshore wind installations. Driven by both policy guidance and market forces, China's offshore wind industry has entered a new phase of scaled commercialization. The 14th Five-Year Plan for Renewable Energy Development issued by the National Development and Reform Commission (NDRC) outlines a future roadmap characterized by cluster-based offshore wind development, large-scale nearshore expansion, and pioneering demonstrations of deep-sea technologies. A fully integrated industrial chain has now taken shape, spanning from upstream high-strength fiber materials and precision manufacturing to downstream sectors such as marine ranching, energy storage, artificial intelligence, and financial leasing. By 2030, China's total ocean wind capacity is projected to reach 200 GW, attracting over RMB 2.6 trillion in investments and generating an industrial output exceeding RMB 20 trillion.

As renewable energy costs decline and subsidy pressures

mount, the National Development and Reform Commission (NDRC) and National Energy Administration (NEA) have progressively advanced subsidy-free policies for wind power. Initiatives emphasizing competitive allocation mechanisms have accelerated the sector's transition into full market-driven competition. Operating without state subsidies entails achieving feed-in tariffs at or below local coal-fired benchmark prices, thereby enabling fair competition with conventional energy. Since 2022, newly approved offshore wind projects have no longer received central fiscal subsidies and must compete directly with local coal-fired power benchmark tariffs. Following the withdrawal of central government subsidies, several provinces have introduced local fiscal support mechanisms to ensure a smooth transition for regional offshore wind projects. For instance, Guangdong's Implementation Plan for Promoting Orderly Offshore Wind Development and Sustainable Industrial Growth (Yue Fu Ban [2021] No. 18) stipulated that provincially managed projects approved before 2018 and achieving full-capacity grid connection between 2022–2024 would remain eligible for subsidies, whereas projects connected after 2025 would not. In January 2025, the Notice on Deepening Market-Oriented Feed-in Tariff Reform to Promote High-Quality Renewable Energy Development (NDRC Price [2025] No. 136) further emphasized that renewable energy grid-connected electricity volume must primarily participate in power market trading. This paradigm shift signifies that future project revenues will no longer rely on static long-term benchmarks, but will instead be subject to the stochastic volatility of market-based trading prices.

With the advent of this subsidy-free and market-driven era, offshore wind investments now exhibit highly dynamic economic and risk characteristics. Existing research, which largely relies on deterministic parameters, often fails to capture the complex uncertainties introduced by market-price volatility, weather-dependent operational costs, and long-term inflation over a 25-year lifecycle. To address these methodological gaps, this study provides a comprehensive risk assessment framework tailored for contemporary investment landscapes. The innovative contributions of this paper include: (1) quantifying the economic viability of unsubsidized projects under stochastic market conditions; (2) developing a dynamic Monte Carlo risk assessment model that logically integrates long-term inflation, floating market tariffs, and weather-sensitive operational risks; (3) identifying key sensitivity factors impacting financial performance; and (4) proposing robust policy and operational recommendations to ensure long-term viability.

The structure of this paper is organized as follows: Section 1 reviews theoretical frameworks for wind project investment decisions and risk assessment; Section 2 develops a stochastic risk assessment model; Section 3 applies the model to a case study and analyzes key sensitivity factors; and the conclusion section provides policy recommendations.

II. LITERATURE REVIEW

A. PROJECT RISK ASSESSMENT

Project risk refers to uncertain events that may affect project outcomes, encompassing both negative and positive impacts [1]. Project risk analysis involves quantifying the probability of such uncertain events and evaluating their effects on investment returns, thereby determining the overall risk exposure level [2]. This risk management process comprises three key phases: risk identification, risk assessment, and risk response. Diverse methodologies exist for project risk assessment, which can generally be categorized into comprehensive risk assessment and investment-specific risk assessment. For comprehensive risk assessment, mainstream methods in recent years include: Analytic Hierarchy Process (AHP), Fuzzy comprehensive evaluation, Fuzzy Analytic Hierarchy Process (FAHP), and Fuzzy Technique for Order Preference by Similarity to Ideal Solution (FTOPSIS). In practical applications, Yuting *et al.* developed a comprehensive risk indicator system with FAHP to assess urban rail transit project risks [3], while Jokar *et al.* utilized fuzzy multi-criteria decision-making techniques to analyze risks in wastewater treatment and renewable energy projects [4].

Traditional methods for investment risk analysis include discounted cash flow (DCF) and sensitivity analysis, while Monte Carlo simulation (MCS) has gained increasing attention in recent years. Although DCF remains widely used for project risk assessment, its accuracy is limited in long-term projects due to insufficient consideration of future cash flow uncertainties [5]. Sensitivity analysis evaluates how variations in key factors affect benefit indicators, thereby identifying critical variables—suitable for assessing single or a limited number of variables in risk models. For complex risk scenarios, MCS demonstrates superior predictive capability by employing probability-based statistical simulations to determine investment risks through uncertainty distribution analysis. Recent studies have applied MCS to calculate internal rate of return (IRR), net present value (NPV), and other metrics for evaluating economic risks in renewable energy, wind power, and wastewater treatment projects [6–10].

For instance, Yeter *et al.* developed a macroeconomic data-driven model that used MCS to analyze the impact of macroeconomic factors on offshore wind project risk management. Additionally, system dynamics and real options approaches are emerging in project risk assessment: Xu *et al.* proposed a system dynamics framework to study investment risks in China's onshore and offshore wind projects. Their findings revealed that offshore projects initially carry higher risks than onshore projects, but this trend reverses in later stage, with dominant risk factors shifting from policy to market risks [11]. Additionally, Hwang and Kim applied real options analysis to conduct techno-economic assessments of floating offshore wind farms in Korea, evaluating project feasibility under multiple uncertainties, including system marginal price, exchange rates, and wind speed fluctuations [12].

B. INVESTMENT DECISION-MAKING AND RISK ASSESSMENT FOR WIND POWER PROJECTS

Investment decision-making and risk assessment constitute critical determinants for the success of wind power project and have long been a focal point in academic research. Scholars have explored this domain through methodological innovations, cost-benefit analysis, and investment strategies. In methodological advancements, Zhang Xiaoyang and Sun Yan introduced the real options approach to offshore wind investment decisions, establishing a pricing framework for deferral and growth options based on the Black-Scholes and binomial tree models [13]. Wuyunna *et al.* constructed a risk indicator system for wind power project investments and developed a risk decision-making model by integrating interval type-2 fuzzy numbers with the AHP-VIKOR algorithm [14]. Regarding cost-benefit analysis, Li Zhixue *et al.* employed the levelized cost of electricity (LCOE) methodology to estimate China's wind power generation costs, revealing an approximate value of 0.3 CNY/kWh with a downward trend. Their analysis identified equipment investment and depreciation as the primary influencing factors [15]. Feng Li *et al.* analyzed offshore wind cost structures and economics from a lifecycle perspective, proposing that optimizing turbine technology, developing deep-sea wind farms, and promoting industrial intelligence are key pathways to enhance economic sustainability [16].

For investment strategies, Liu *et al.* formulated a two-dimensional binomial lattice framework to simulate how dynamic subsidy adjustments influence investment decisions under uncertainty [17]. Wang Hui and Wu Zichao analyzed wind power investment environments through policy-market dual dimensions, proposing strategies including "certificate-electricity integration," "policy-driven foundations," and "wind-storage hybrid systems" [18]. In the context of grid-parity wind power, some scholars have focused on economic feasibility and investment decision-making of wind power projects. Lou Qihe *et al.* analyzed the key factors influencing the economic performance of renewable energy generation under grid-parity conditions. Their calculations revealed that wind power projects in the "Three North" regions (Northeast, North, and Northwest China) as well as in Shandong, Jiangsu, Fujian, and Shanghai achieved an internal rate of return (IRR) exceeding 8.3%, demonstrating their feasibility for grid parity operation [19]. Wang Xiaoli *et al.* demonstrated that increasing turbine unit capacity by over 50% could enhance returns by 6%–11%. Zhao Rui and Chen Ying investigated how turbine prices, loan rates, unit investments, annual equivalent utilization hours, and Guangdong's subsidy policies affect project returns [20].

In summary, while current studies have achieved notable advancements in economic evaluation methodologies and investment decision modeling for wind power projects, research remains inadequate in addressing the emerging economic challenges and risk landscape of offshore wind power under grid parity conditions. The existing literature predominantly focuses on economic assessments under sub-

sized scenarios, while largely neglecting the identification and quantitative evaluation of risk drivers under new market mechanisms—such as electricity market volatility and competitive allocation—following the phase-out of subsidies.

III. MODEL CONSTRUCTION

A. RISK FACTOR IDENTIFICATION AND PROBABILITY DISTRIBUTION

The economic performance of offshore wind power projects is susceptible to fluctuations in factors such as feed-in tariffs, turbine costs, and power generation output. Before applying the Monte Carlo method, it is essential to distinguish between deterministic parameters and stochastic parameters in the model, and assign probability distributions to the latter.

Key Deterministic Parameters

(1) Construction and Operational Periods Due to the absence of cash inflows during the construction phase, project investors are under significant pressure to complete the project on schedule. Therefore, both the construction period (typically 2 years for offshore wind projects) and operational period (25 years) are treated as deterministic parameters in this analysis, consistent with industry standards.

(2) Equity Ratio Banks generally require a minimum equity ratio of 30% in practice. Therefore, the equity ratio (30%) and loan ratio (70%) are treated as deterministic parameters.

(3) Tax Rate Statutory tax rates (such as the phased Corporate Income Tax incentive scheme) remain stable over long periods and are therefore classified as deterministic parameters. However, it is crucial to note that while the tax rate itself is fixed, the actual annual taxable income is a dynamic function of stochastic variables, primarily generation volume and market-clearing prices. Consequently, the final tax cash flow in our simulation is dynamically generated rather than treated as a simple static constant, thereby more accurately reflecting fiscal risk.

Key stochastic/Uncertain Parameters

(1) Feed-in tariff: During the 13th Five-Year Plan period (2016–2020), China accelerated offshore wind development through tariff subsidies. Starting in 2021, newly approved projects transitioned to subsidy-free grid parity. In the current market-driven era, project revenues are subject to the volatility of market-based hourly or monthly trading prices rather than a static long-term benchmark. Therefore, while the local coal-fired benchmark price (e.g., RMB 0.43/kWh) serves as the expected baseline under grid parity, the actual feed-in tariff is modeled as a stochastic variable with a specified coefficient of variation to reflect market price volatility.

(2) Grid-connected electricity volume: It serves as the core economic variable for offshore wind projects, with its determinacy subject to complex multi-factor influences. Theoretically, generation volume is calculated based on a wind farm's installed capacity; however, the actual annual volume is not a fixed value but rather a dynamic parameter with significant uncertainty.

(3) Static investment: It comprises auxiliary construction works, equipment procurement & installation, civil engineering works, and other associated expenses, where wind turbines account for 51%, and infrastructure construction constitutes 27% of total expenditures [19], while turbine costs declined from RMB 5,200/kW to RMB 3,000/kW during the 14th Five-Year Plan period.

(4) Operating costs: The power generation costs of offshore wind farms primarily include material expenses, basic labor wages, maintenance and repair fees, insurance premiums, and vessel leasing costs. While certain components such as basic salaries can be treated as deterministic constants, offshore-specific operational expenditures—particularly marine maintenance and vessel leasing—are highly sensitive to stochastic weather conditions such as wind speed and sea state. To capture this major offshore-specific risk, operating costs are modeled as stochastic variables with an assigned coefficient of variation.

(5) Loan interest rate: Project loan rates follow the 5-year LPR benchmark (currently 3.5% for 5-year and above terms), adjusting with market capital supply-demand fluctuations.

(6) Project discount rate and equity discount rate: The discount rate is the interest rate used to calculate the present value of future cash flows, reflecting the cost of capital or industry benchmark return. Both the project discount rate and equity discount rate vary with market conditions. With reference to the methodology in Literature 21, the calculated cost of equity capital for the offshore wind power industry is 10%, while the project cost of capital is 5% [21].

(7) Long-term Inflation: A significant oversight in traditional static grid-parity models is the failure to account for inflation over a 25-year operational lifecycle. In this study, to maintain logical consistency and avoid underestimating long-term cost escalation, a long-term annual inflation rate is incorporated into the dynamic operating cost projections and cash flow discounting processes.

B. INVESTMENT RISK ASSESSMENT MODEL

This study develops NPV-at-Risk and IRR-at-Risk models using Monte Carlo simulation to generate cumulative probability distributions of NPV and IRR, evaluating investment risks at specific confidence levels. The specific process involves:

- 1) Segregate parameters into deterministic and stochastic variables.
- 2) Assign expected values, standard deviations, and probability distributions to stochastic parameters. Subsequently, perform multiple iterations with randomized parameter sampling to generate NPV/IRR outcome arrays. Thereafter, derive cumulative probability distributions.

Financially, costs include construction investment, construction-period interest, and total operational expenditures, whereas revenue comes from electricity sales income.

$$NPV = \sum_{t=1}^{t_c} \frac{-I_t}{(1+r)^t} + \sum_{t=t_c+1}^n \frac{R_t - C_t}{(1+r)^t} \quad (1)$$

$$0 = \sum_{t=1}^{t_c} \frac{-I_t}{(1+IRR)^t} + \sum_{t=t_c+1}^n \frac{R_t - C_t}{(1+IRR)^t} \quad (2)$$

Investment risk is defined as $\delta_{NPV < 0}$ and $\delta_{IRR < \overline{IRR}}$. The NPV-at-Risk model:

$$\delta_{NPV < 0} = \int_{-\infty}^0 pdf(y_{NPV}) dy_{NPV} \quad (3)$$

The IRR-at-Risk model:

$$\delta_{IRR < \overline{IRR}} = \int_0^{\overline{IRR}} pdf(y_{IRR}) dy_{IRR} \quad (4)$$

Where,

t_c : construction period

r : Project cost of capital (or equity cost of capital)

R_t : cash inflow in year t

C_t : cash outflow in year t

IRR : internal rate of return

NPV : net present value

I_t : total investment.

IV. PROJECT BACKGROUND

A. PROJECT OVERVIEW

Given Guangdong Province's critical role in China's offshore wind power development, this study selects an offshore wind power project in the province as a case study. The project covers an area of approximately 160 km², with an average annual wind speed of 8 m/s and a planned installed capacity of 1,000 MW. It comprises a total of 72 wind turbines, each with a unit capacity of 14 MW. The wind farm is situated approximately 60 km offshore, where water depths range from 40 to 48 m. The construction period is 2 years, and the operational period is 25 years.

Project Cost Analysis: The static investment amounts to RMB 120.0672 billion, while the dynamic investment totals RMB 123.4672 billion, including RMB 300 million in construction-period interest. The debt-to-asset ratio stands at 70%, with a loan interest rate of 3.5%. The projected annual grid-connected electricity volume is 3,360 GWh, while the regional grid parity electricity price is estimated at RMB 0.43/kWh.

Project Economic Assessment: Conducted in accordance with the Economic Evaluation Standards for Wind Power Projects issued by the National Energy Administration, the economic assessment demonstrates the following results: Post-tax financial internal rate of return (FIRR) for the project: 5.5% (similarly hereafter); post-tax FIRR for equity capital: 13.28%. Post-tax financial net present value (FNPV, discount rate 5%): RMB 58,675.27 million; equity FNPV (discount rate 10%): RMB 12,430.828 million.

Static payback period: 14.7 years; total investment return rate: 5.1%; equity net profit rate: 8.7%, indicating financial feasibility. Average interest coverage ratio during the repayment period: 5.71; debt service coverage ratio: 1.25, demonstrating adequate debt repayment capacity.

B. DATA COLLECTION

This study combines literature review and expert consultation to determine the probability distributions, means, and standard deviations of various variable factors, thereby establishing the key parameter settings for the model. **Deterministic Factors** The equity ratio is set at 30%, with a construction period of 2 years and an operational period of 25 years. The residual value rate of fixed assets is 5%, depreciated over 25 years using the straight-line method. In compliance with the Notice on Wind Power Value-Added Tax Policies (Cai Shui [2015] No. 74) issued by the Ministry of Finance and the State Taxation Administration, the VAT rate for wind power is 13%, with 50% refunded upon collection. Corporate income tax (CIT) incentives follow a phased scheme: Years 1–3 enjoy full exemption (0% CIT) from the first fiscal year of revenue generation; Years 4–6 apply a 12.5% reduced rate (half of standard 25%); the standard 25% rate takes effect from Year 7 onward. **Variable Factors** Key assumptions include:

Expected grid-connected electricity volume: 3,360 GWh (coefficient of variation, CV: 0.05).

Expected feed-in tariff: 0.43 RMB/kWh (CV: 0.1).

Expected static investment: RMB 120.0672 billion (CV: 0.05).

Expected working capital: RMB 40 million (CV: 0.1). Expected long-term and working capital loan interest rates: 3.5% (CV: 0.15 for both). Expected material costs, annual salary per capita, and other expenses: RMB 30/kW, RMB 100,000/person, and RMB 40/kW, respectively (CV: 0.1 for all).

Expected equity discount rate: 10% (CV: 0.1). Project discount rate calculated using the weighted average cost of capital (WACC).

C. SIMULATION RESULTS ANALYSIS

A Monte Carlo simulation (MCS) model in Excel was employed to conduct 5,000 simulations for all parameters, generating cumulative probability distribution graphs for net present value (NPV) and internal rate of return (IRR): Figure 1 shows the cumulative probability distribution of the project's post-tax NPV, with a 69.63% probability of NPV > 0. Figure 2 presents the cumulative probability distribution of the equity post-tax NPV, with an 88.16% probability of NPV > 0. Figure 3 displays the cumulative probability distribution of the project's post-tax IRR (benchmark: 5%), showing a 65.15% probability of exceeding the benchmark. Figure 4 illustrates the cumulative probability distribution of the equity post-tax IRR (benchmark: 10%), with a 90.56% probability of exceeding the benchmark.

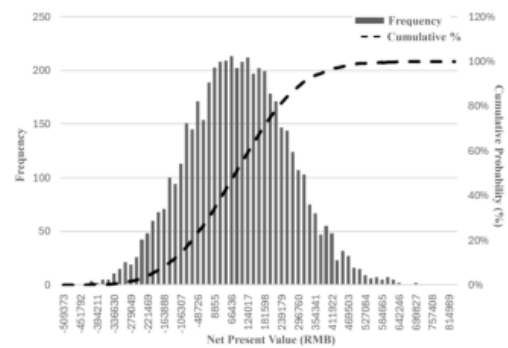


FIGURE 1. Cumulative probability distribution of project investment NPV

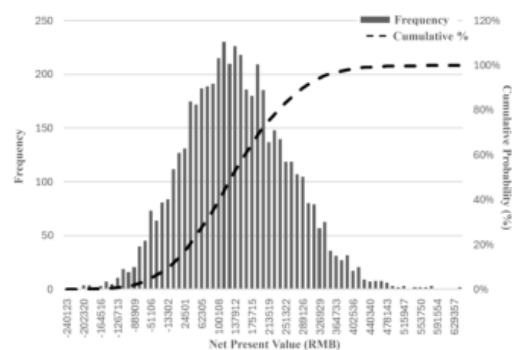


FIGURE 2. Cumulative probability distribution of equity investment NPV

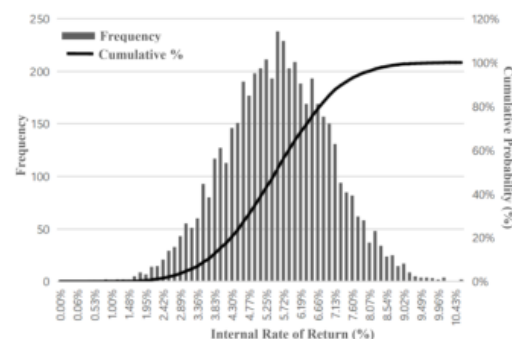


FIGURE 3. Cumulative probability distribution of project IRR

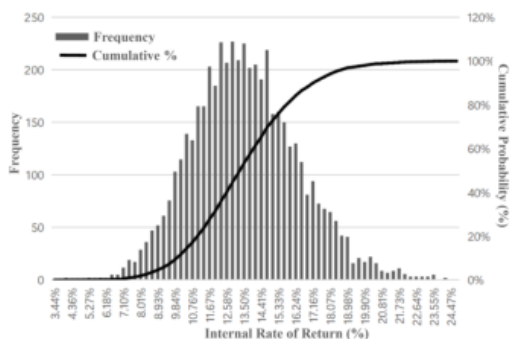


FIGURE 4. Cumulative probability distribution of equity IRR

This relatively high probability should be interpreted with caution rather than as evidence of uniformly low risk. The comparatively optimistic equity IRR distribution mainly results from the leveraged financing structure of the case project, where debt financing accounts for 70% and equity financing accounts for 30%. Under this capital structure, the return on equity is amplified once operating cash inflows remain broadly stable. In addition, the current simulation is based on the assumed statistical ranges of key variables, including grid-connected electricity volume, feed-in tariff, static investment, and financing costs. Therefore, Figure 4 reflects the equity-return distribution under the model assumptions of this case, rather than a universally optimistic outcome for all grid-parity offshore wind projects. Nevertheless, this result does not imply that equity investors face limited downside exposure. As shown by the sensitivity analysis, equity returns remain highly sensitive to changes in electricity volume, feed-in tariff, and static investment. If adverse market price movements, curtailment, construction cost overruns, or financing-condition deterioration are more severe than assumed, the equity IRR distribution would shift leftward significantly. Hence, the high probability of equity IRR exceeding 10% should be understood as conditional on the current assumptions and financing structure. The results suggest that the project is financially feasible under the current assumptions; however, the relatively optimistic equity-side return distribution should be interpreted as conditional on the assumed parameter ranges and financing structure.

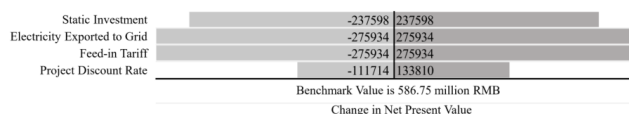


FIGURE 5. Key factors influencing project cash flow

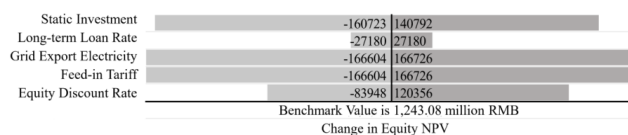


Figure 6. Key factors influencing equity cash flow

FIGURE 6. Key factors influencing equity cash flow

D. KEY RISK FACTORS AFFECTING OFFSHORE WIND POWER INVESTMENTS

A tornado diagram visually illustrates the key sensitivity factors influencing the project's Net Present Value (NPV). Figure 5 presents the sensitivity analysis results of the project's NPV under $\pm 20\%$ fluctuations in key parameters, identifying four key sensitivity factors: grid-connected electricity volume, feed-in tariff, static investment, and project discount rate. The analysis reveals significant variations in NPV sensitivity:

- 1) Primary sensitivity factors: Feed-in tariff and grid-connected electricity volume show the highest sensitivity. A $\pm 20\%$ change results in NPV fluctuations of $\pm$ RMB 27.5934 billion. This demonstrates that project profitability is highly dependent on future power generation and electricity pricing.
- 2) Secondary sensitivity factor: Static investment shows an inverse correlation. A $\pm 20\%$ variation causes opposite NPV movements of RMB 23.7598 billion, indicating that capital expenditure is a key project economics driver.
- 3) Asymmetric impact: Project discount rate creates non-linear effects: a $+20\%$ change reduces NPV by RMB 11.1714 billion, while a -20% change increases NPV by RMB 13.3810 billion.

Other factors (e.g., labor costs, material expenses) exhibit negligible impacts on NPV and are therefore excluded from detailed discussion.

Figure 6 presents the sensitivity analysis of equity financial net present value (FNPV) under $\pm 20\%$ fluctuations in key parameters from the equity perspective. The primary sensitivity factors are, in descending order: grid-connected electricity volume, feed-in tariff, static investment, equity discount rate, and long-term loan interest rate.

Key findings:

- 1) Primary sensitivity factors: Grid-connected electricity volume and feed-in tariff exhibit the strongest impact on equity FNPV. A $\pm 20\%$ variation causes corresponding changes of $\pm$ RMB 16.6726 billion or $\pm$ RMB 16.6604 billion from the baseline, confirming that shareholders' profitability and risk resilience are highly dependent on operational revenue performance.

- 2) Secondary yet non-negligible sensitivity factors include static investment and the equity discount rate. Regarding static investment, a 20% increase reduces equity NPV by RMB 16.0723 billion while a 20% decrease increases it by RMB 14.0792 billion, revealing that the more pronounced negative effect from cost increases underscores the critical need for rigorous cost control during the construction phase.

As for the equity discount rate, a 20% increase in the rate reduces equity NPV by RMB 8.3948 billion while a 20% decrease in the rate raises equity NPV by RMB 12.0356 billion, indicating that the current accommodative financing conditions are lowering capital costs, thereby enhancing the project's overall financial viability.

3) Marginal sensitivity factor covers long-term loan interest rate. Specifically, a 20% interest rate increase reduces equity NPV by RMB 2.7180 billion while a 20% decrease increases it by the same amount, indicating that the current low-interest-rate environment continues to alleviate debt servicing pressure for shareholders.

Labor costs, material expenses, and other variables with negligible impact are omitted from further analysis. In summary, the economic viability of this project primarily depends on future operational revenue, followed by initial investment costs and financing costs.

V. CONCLUSIONS AND RECOMMENDATIONS

This study investigates the economic viability and investment risks of unsubsidized grid-parity offshore wind power projects by developing dynamic, stochastic NPV-at-Risk and IRR-at-Risk investment risk assessment models. Addressing the limitations of traditional deterministic approaches, our enhanced models explicitly account for long-term inflation over the 25-year operational lifecycle, the volatility of market-based trading prices, and the weather-sensitive stochastic nature of marine maintenance and vessel leasing. These models were then applied to a grid-parity offshore wind project in Guangdong Province for simulation analysis. Through a Monte Carlo simulation with 5,000 iterations, the cumulative probability distributions of NPV and IRR were obtained, thereby identifying investment risks. The simulation results suggest that, under the assumed parameter ranges and financing structure, the project remains financially feasible; however, the relatively optimistic equity-side return distribution should not be interpreted as indicating uniformly low investment risk. Moreover, the models prove highly effective in assessing offshore wind project risks, providing a comprehensive risk evaluation framework that captures the true stochastic nature of operating cash flows and taxable income. These findings offer significant practical guidance for investment decision-making and risk management in similar offshore wind projects.

A limitation of this study is that the simulated equity IRR distribution depends on the assumed probability distributions and coefficients of variation of key inputs. If future market-based electricity prices, generation uncertainty, construction cost escalation, or financing conditions deteriorate beyond the assumed ranges, the actual equity return performance may be materially lower than the results reported here. Additionally, further analysis identifies the key sensitivity factors affecting the project's financial net present value (FNPV), namely grid-connected electricity volume, feed-in tariff, and capital investment. Based on these findings, targeted risk management strategies are pro-

posed for three core stakeholders: government agencies, investors, and lenders.

Risk Management Strategies for Government Agencies

For local governments, the offshore wind industry represents a high-investment, long-industrial-chain sector with strong economic spillover effects, serving as both a key driver for high-quality regional economic growth and a strategic emerging industry within the modern industrial system. To ensure the stable development of the offshore wind sector, government agencies should adopt the following measures:

- (1) Formulate clear, long-term, and stable market-trading mechanisms and green certificate policies to help enterprises offset price volatility risks and stabilize revenue expectations;
- (2) Optimize the investment environment by streamlining project approval procedures, improving administrative efficiency, and providing infrastructure support and tax incentives to help enterprises control initial costs;
- (3) Promote industrial clustering, including the collaborative development of offshore wind and high-performance fiber-reinforced material industries, through establishing offshore wind industrial parks and attracting core enterprises across the supply chain. This will facilitate resource integration across the industrial chain, reduce equipment logistics and technical service costs through agglomeration effects, and enhance the overall competitiveness of local industries.

Risk Management Strategies for Investors

For investors, the critical sensitivity factors affecting cash flows include grid-connected electricity volume, feed-in tariff, construction investment, and capital costs. To mitigate risks, the following strategies are recommended:

- (1) **Enhance operational efficiency and management:** It is essential to prioritize project operation management and efficiency. This can be achieved by deploying intelligent weather-forecasting systems to optimize marine maintenance schedules and reduce vessel leasing uncertainties, selecting high-performance equipment, establishing an operation and maintenance team, and dynamically monitoring operational performance to ensure stable annual power generation.
- (2) **Address market risks in feed-in tariffs:** Prioritize signing long-term power purchase agreements and actively participating in green electricity trading to mitigate future tariff volatility risks. Explore integrated development models such as "offshore wind power+ marine aquaculture," "offshore wind power+ coastal tourism," "offshore wind power + hydrogen production from seawater" to enhance the economic efficiency of marine resource utilization.
- (3) **Control construction investment costs:** Construction investment costs must be strictly controlled through lean management practices. Investors should pay close attention to technical upgrades and price fluctuations of core components to minimize budget overruns. Strengthen supervision throughout the project lifecycle, rigorously manage invest-

ment budgets, and establish mechanisms to address cost overruns.

(4) Optimize financing strategies: Take advantage of the current accommodative financing environment and low capital costs by leveraging debt to improve return on equity. Avoid excessive debt; maintain proactive communication and cooperation with lenders, selecting more favorable and flexible financing solutions to reduce capital costs.

Risk Management Strategies for Lenders

As the stakeholder with the lowest risk tolerance, lenders has the core objective of risk management to ensure absolute security of both loan principal and interest. The following measures are recommended to mitigate risks:

(1) Credit approval & disbursement phase: During the credit approval process, lenders must thoroughly evaluate the operational performance of the equipment, verify whether the project has long-term and stable power purchase agreements to hedge against market-price volatility, and actively utilize syndicated loans to diversify risks. Additionally, throughout the construction phase, lenders must closely monitor project progress, require the enterprise to provide completion guarantees or completion bonds, disburse funds in stages according to construction milestones, and strictly supervise the use of loan funds.

(2) Operational phase monitoring: During the project operation period, the lender should establish a continuous monitoring mechanism, with a particular focus on actual grid-connected electricity generation, market-driven feed-in tariffs, and inflation-adjusted operating cash flows. If persistent deviations occur, risk warnings should be promptly trigger.

(3) Financial innovation & risk modeling: Banks should actively explore and adopt green credit instruments while striving to improve dynamic, stochastic project risk assessment models that account for long-term climatic and market uncertainties.

AUTHOR CONTRIBUTIONS

Conceptualization – Xie S and Tan J; methodology – Xie S; formal analysis – Tan J; investigation – Xie S; resources – Xie S; writing-original draft preparation – Xie S; writing-review and editing – Tan J; visualization – Tan J; supervision – Xie S. All authors have read and agreed to the published version of the manuscript.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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